The use of borehole radiation detectors for mineral exploration dates back more than 60 years. The natural gamma log is one of the most common borehole measurements and continues to be an important part of any exploration program. The recent increase in the demand for nuclear reactor fuel has created a boom in exploration and appraisal drilling of uranium prospects. The basic physics of borehole gamma detection has not changed drastically over the years, but the instrumentation, and data acquisition and processing methods have.

In general, downhole gamma detectors fall into two categories, based on the application. For gross gamma logging, Geiger-Mueller tubes and scintillation detectors are most often used. For spectroscopy work, scintillometers are favored, and high-resolution multichannel analyzers complete the package.

In the early days, Geiger-Muller detectors were used because they were extremely rugged, low cost, and easy to build. A simple high voltage power supply with gain control allowed an operator to tune a detector such that it could operate on a relatively flat voltage “plateau”. A drawback of G-M tubes is that they take a fair bit of time to register one pulse of ionizing radiation. This instrument measuring time (during which no other event can be registered) is often called “dead-time”, because the sensor is effectively unable to measure during that time. A typical dead-time for a G-M tube is around 100 microseconds. This effectively limits the maximum counting rate of a single tube to around 10,000 cps. Since most commercial uranium ore bodies have radiation greater than this, these detectors cannot easily be used or calibrated over a wide range of ore grades. In modern applications of G-M tubes, special models have been developed that operate in a range where they can be used in very high grades (5-35% eU3O8), producing count rates between 500 and 3500 cps. At these count rates, there is very little non-linearity across the grade range.

For exploration work, NaI(Tl) scintillation detectors are most often used. The volume of the crystal is generally matched with the expected grade, so that smaller (and often shielded) crystals are used for higher grade prospects. For lower grade ores, a larger detector is used to improve on the precision of the grade determination. Such detectors have a volume of around 29.5 cc.

The simplest probes consist of a detector, plus a high voltage power supply with pulse conditioning circuitry in the probe that effectively sends varying frequency pulses up an insulated logging cable. The pulses, whose shape and size are diminished due to signal loss during transmission, are discriminated, counted and sent to a display or data recording device at the surface. In the early days of uranium exploration, this analog method of counting radioactivity led to an esoteric procedure for presenting the results. Many factors had to be considered in extracting useful data from the results. Probes had to be calibrated at known models that produced repeatable results. Logging systems were often re-calibrated when logging cable type or length changed. Such calibrations gave rise to complicating factors, such as total dead-time, casing factors, water factors, etc. and the calibration constant or k-factor. A large volume of published work discusses these procedures in great detail. Some of these calibration tasks are still required for modern measurements, but many have become less important due to advances in probe design and processing methods.
Analog pulse transmission is still used by many gross gamma systems. As long as the instrument is calibrated often and the components of the system are not changed, such systems can produce accurate results. The behavior of the system (power supplied to probe, signal degradation during pulse transmission up the cable, and level of uphole pulse discriminators) must not change or the calibration may not be correct.

To eliminate this problem, modern probes have constant output, continuously monitored downhole power supplies, and digital counting circuitry. The data (pulses) from the probe are counted in the probe by extremely stable pulse discriminators, and the results are then fed to an in-probe counter whose output is fed to a digital coding processor that sends the data up the wire-line as either a frequency or pulse modulated signal. The information is embedded as binary data, consisting of ones and zeroes, and the results are then decoded with matching circuitry at the surface unit. Hence, there is no possibility of signal degradation or missed pulses. An additional advantage of downhole digitization of the detector signals is that additional sensors and detectors can be added to the probe string to allow more information to be recorded on a single logging pass.

For example, if an exploration target was expected to contain high and lower grade ore, a digital probe with a high resolution NaI scintillation detector and a lower counting G-M detector would be desirable. An example data set from a multi-detector digital probe logged in northern Saskatchewan is shown below:

This digital probe contains two GM tubes whose output is summed to provide a near direct readout of ore grade in higher grades. The GM tubes have low sensitivity and resolution in the lower grade ore, where the NaI detector provides better results. The NaI detector is not well suited to the higher grade ore, since the instrument dead-time requires a large correction factor which is non-linear over the grades in this drill hole.

Such multi detector, multi-sensitivity probes are ideal for areas where known higher grade ore will be intercepted, but lower grade ore is also of interest. The multiple detector package minimizes the number of logging runs and probes required.
The use of digital multichannel spectral probes has grown in recent years. Passive spectral probes were originally used for determining the relative amounts of K, U, and Th in sediments. The data was processed to predict different clay/mineral fractions in oil and gas reservoirs. In uranium exploration, it is often necessary to determine if other radionuclides, such as Th, are present in an exploration target, for resource evaluation. It is also possible to use a spectral probe, isolated on one of the main U energy windows, to determine ore grade. Later in this paper a new detector type will be discussed that may be able to predict disequilibrium using a spectral probe.

A spectral probe has a scintillation detector that must be thermally stabilized so that the individual energies of each incoming gamma can be measured. A downhole multichannel analyzer counts the pulses coming into preset energy bins, to allow separation of U events from K, or Th (the other natural occurring radioactive minerals).

By analyzing the net counts in a selected U window, and comparing to results from known models, ore grade can be determined. Gross count tools do not need temperature stabilization, but spectral tools require this. Most detector material has light output (the photon energy produced by the incoming gamma ray) that varies with temperature. This is important consideration in the calibration and operation of spectral tools.

An example of a typical uranium spectrum from a NaI based spectral probe follows:

![Spectrum statistics options](image)

The shaded area shows the “standard” uranium window, dominated by energies from the 1764 and 2204 keV. The spectral probe allows isolation of this energy range. By removing the Compton edge (the piled up lower energy pulses on the left side of the display, it is possible to get more accurate grade calculations with a spectral probe. The figure below shows an example from the U2 model at the US DOE calibration facility in Grand Junction, CO, USA, illustrating the total counts, spectra, and counts from the U energy window.
By using the U window counts for a range of models, a polynomial best fit line can be developed for U ore grades vs. windowed cps. The chart on the next page shows how this can be determined using a standard spreadsheet program. This method of determining grade directly also applies to gross count probes, and has been used successfully in many field areas. This direct cps to grade processing eliminates the intermediate steps of calculating a dead-time for each probe and pit configuration. It also removes the confusing k-factor calculation and application from the process.

Corrections will still need to be made for wet vs. dry hole conditions and casing or drill steel influence. But processing with curve fitting over a range of grades using PCs is a vast improvement over the older k-factor based methods.
The polynomial equation above can be applied to the raw probe data (in this case to the counts in the spectra U window from 1650 to 2390 kEv), to arrive at direct grade estimates. The log example below shows a result of this process on actual field data.
A new type of scintillation detector is undergoing field trials in Australia and the US. It is made from Lanthanum Bromide (LaBr₃(Ce)). This material has much higher resolution than NaI or BGO and is more stable with temperature. It is anticipated that this new detector will provide more precision in common spectral measurements, and allow estimation of disequilibrium.

This will be accomplished by taking the ratio of the various peaks associated with the different daughter products in ore that is not in equilibrium.

An sample uranium spectra is shown below, comparing responses from the most common scintillation detectors, plus a laboratory germanium detector.

(from Geotron presentation, 2006).

The new material is only being produced in two locations, and patents have kept the relative cost high compared to other detectors. But if the LaBr₃(Ce) detectors provide the resolution and performance as advertised, the uranium exploration community may see a new family of instruments in the near future.